Using Y-source network as a connector between turbine and network in the structure of variable speed wind turbine

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ABSTRACT

Environmental factors such as air pollution and increase in global warming by using polluting fuels are the most important reasons of using renewable and clean energy that runs in global community. Wind energy is one of the most suitable and widely used kind of renewable energy which had been in consideration so well. This paper introduces an electric power generation system of wind based on Y-source and improved Y-source inverter to deliver optimal electrical power to the network. This new converter is from impedance source converters family. This presented converter has more degrees of freedom to adjust voltage gain and modulation. Also, by limiting the range of simultaneous control (shooting through) while it maintains the highest power of maximizer, it can operate in higher modulation range. This causes the reduce of stress in switching and thus it will improve the quality of output. Recommended system had been simulated in MATLAB/Simulink and shown results indicate accurate functionality.

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1. INTRODUCTION

Using clean and renewable energy had been major concern for global communities and been introduced as an important and vital matter. Environmental factors such as air pollution and increase in global warming by using polluting fuels are the most important reasons of using renewable and clean energy. Another advantage of using renewable energy sources is minimizing the size of power production units and increasing the distributed generation units, the proximity of the units of production and consumption of electric power and thus reduce losses and increase efficiency [1]–[22]. One of the highly used renewable energy that had been in consideration is wind energy [1], [4], [14], [16], [19], [20], [23], [24]. Using wind energy specially in windy areas in addition to the economic saving, increased quality will also be delivered. Electric power generation system from wind energy has been divided into 4 parts: i) wind turbine, ii) electric generators, iii) power electric devices, and iv) controlling systems. Which by increase in this industry and technology there has been much progress in these sections and power electric devices, different generators and control systems had been presented [25]. For example, with progress in materials science and further showing off the permanent magnet machines, using wind energy in different speed without gearbox is highly regarded. Thus, study of the electrical power generator systems from wind energy based on stimulating converters with permanent magnet is essential from different points of view.

In the field of power electronic devices, there had been more different suggestions with unique features presented which the most important one is using one boost converter and source voltage inverter. Electric power generation systems from wind energy with different speed has many positive features such as: small size, high efficiency, lower installation cost and lower maintenance cost, compare to systems with fixed speed. Considering permanent magnet generators (PMGs) that can connect to the network directly and without using gearbox, has attracted more attention [26]–[31]. Hence, the purpose of this paper considering the importance of the power electric devices in delivering electric power to the network (connector between wind turbine and the network), is to suggest using Y-source network in variable speed wind turbine systems based on permanent magnet machines as electronic converter. Mainly voltage source inverters only can show buck performance (reducing) as a result, the AC output voltage will be limited by DC voltage source. Also, in renewable energy applications input DC voltage fluctuates in a wide range and so there is need for buck-boost function. To overcome this problem, firstly we use DC/DC converter which it is placed between the source and inverter. By adding a DC/DC converter the structure will have two stages. In two stages structure due to the lack of optimum combination, efficiency of the system and its performance will extremely reduce. To fix these problems, impedance source inverter had been introduced, while they are single-stage due to the removal dead time solving the DC bass short connection problem, they have high reliability. By introducing these converters study field of many such as modulation, modeling, control is provided for the converters [32]. Although buck-boost converter topology which is used to convert DC/AC as theory can boost the voltage to any desired value, but the ability of these converters boosting will be limited by passive elements and all the factors [33]. Specially in high duties of self-charging current cause massive losses in passive elements and this cause instability and limiting the boost of voltage. Impedance networks cover the entire range of power electronics, converting completely from converter and rectifier to converting phase and frequency. There have been many different structures to solve limitations and problems of traditional structures of voltage source and current source for impedance network converters in [4][34]–[37]. Placement and proper implementation of the impedance supply network with switching and the appropriate setting, reduce the power converting levels in power system chains. This improves reliability, stability and improvement and also efficiency. The general scheme of impedance source converters structure with different switch for different applications is shown in Figure 1 [32], [38].

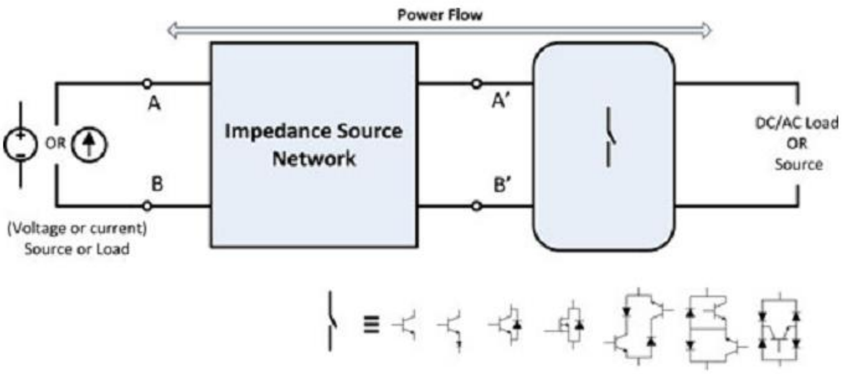


Figure 1. General scheme of impedance source converters structure with different switch for different applications [3]

So far, there has been many impedance source networks with the ability of maximizing which the most important one is Z-source [39]–[46]. Features of this converter let researchers to think about solving the problems of this structures and present structures like quasi-Z, embedded-Z, tapped-inductor, T-source, Γ-source impedance source. Y-source converter has been introduced recently and is used as DC/DC and AC/DC with three coils which had been coupled [34]. This converter has many different features. The interest of this converter in equal duties is different to other converters and has more freedom to (the number of turns of coils and switch timing (d_{st})) adjust the interest of voltage compare to classic impedance source converters [34], [47]. Theoretical point of view, by adjusting the number of turns in coils $d_{st}$to any value, we can see the increase in voltage [23]. In the following proposed system, variable speed wind turbine based on Y-source inverter has been investigated and the results have been provided.

2. THE PROPOSED WIND TURBINE SYSTEM

Proposed system based on Y-source inverter and permanent magnet synchronous generator (PMSG) shown in Figure 2. In the following, we will discuss different parts of the proposed system.

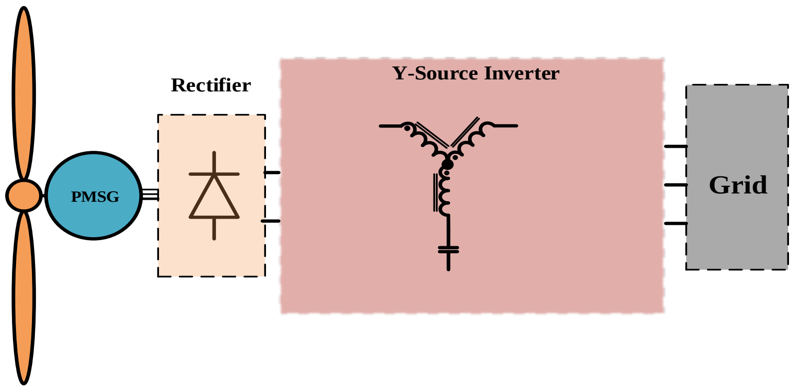


Figure 2. proposed system scheme

2.1. Modeling of wind turbine

To obtain a proper expression of wind energy, this energy must be measured in some way. Calculating this energy with simple rules of classical physics, the kinetic energy of wind will be calculated as (1).

$$E_{wind} = \frac{1}{2} m V_w^2 \quad (1)$$

In this equation m is equivalent to mass of a volume of air passing through the turbine. It is assumed that the total volume of wind moving at the same speed of V_w. Wind speed unit is meter per second m/s assuming constant speed of volume of wind hitting turbine blades, and a period of time t. We can define the mass as (2).

$$m = \rho A V_w t = \rho \pi R^2 V_w t \quad (2)$$

which ρ is air density, A the area swept by the turbine blades and R is the radius of the turbine blade. Substituting (2) in relation (1) to the kinetic energy of the wind will be expressed as (3).

$$E_{wind} = \frac{1}{3} \rho \pi R^2 {V_w}^3 t \quad (3)$$

Using (3), the real power in wind power in every moment of time will be calculated as (4).

$$P_{wind} = \frac{E_{wind}}{t} = \frac{1}{2} \rho \pi R^2 {V_w}^3 \quad (4)$$

This (4) shows that wind energy is heavily dependent on the wind speed. The affiliation with the cube of wind speed is specified. So, a slight change in wind speed will create significant change in wind energy. Also, it is possible to get more energy from the wind by increasing the radius of the turbine blades. However, calculated power in (4) is the potential of wind power which is been calculated in wind speed V_w and R radius of turbine blade. From this amount, only a portion of that is converted into mechanical energy. This percentage will be calculated as Albert Betz determined in 1919 by presenting this method [48]. Based on this method, when the turbine blades are in wind direction, the wind speed reduce, as a result received energy by turbine will be less than maximum energy in the wind speed. The relationship between received energy by turbine, $P_{turbine}$, and maximum energy of wind, P_{wind}, and power factor of wind turbine, C_p, is as (5).

$$C_p = \frac{P_{turbine}}{P_{wind}} \quad (5)$$

This ratio is calculated as [7]:

$$C_p = c_1(c_2\frac{1}{\alpha} - c_3\beta - c_4\beta^x - c_5)e^{-c_6\frac{1}{\alpha}} \quad (6)$$

$$\frac{1}{\alpha} = \frac{1}{\lambda+0/08\beta} - \frac{0/035}{1+\beta^3} \quad (7)$$

$$\lambda = \frac{\omega_m R}{V_W} \quad (8)$$

In (6), (7) and (8), β is the angle of rotor blade which is shown in the Figure 3. λ is the severity rate of speed of wind turbine and ω_m is angular velocity of the generator and wind turbine. Constant values (c_1 and c_6) depend on type of turbine [49]. In the angle $\beta = 0$ maximum power is available.
At the end the equation of turbine blade is as (9).

$$P_{turbine} = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta){V_W}^3 \quad (9)$$

Turbine mechanical torque, T_m, is obtained from (10).

$$T_m = \frac{\frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)V_W^3}{\omega_m} \quad (10)$$

The following will be the simulation of wind, the effect of β on C_p has been investigated and ratio of highly optimized speed λ_{opt}, which $C_{p_{opt}}$ is produced because of that, had been calculated. To gain this goal C_1 to C_6 parameters as Table 1. To simulate the wind, in here we have used linear form which is like increasing and decreasing of gradient.

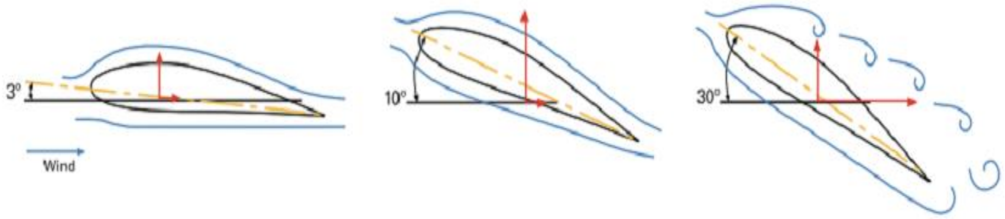


Figure 3. Turbine blade's angle diagram.

Table 1. C1 to C6 constants

C_1	C_2	C_3	C_4	C_5	C_6
0/5	116	0/5	0	5	21

2.2. Modeling of permanent magnet synchronous generator (PMSG)

The dynamic model of electric machines is necessary for investigating the dynamic conditions and potential errors. Dynamic modelling based is on voltage equations, flow, flux-flow and park conversion. In electric machines depends on input and output variables, different models can be simulated. In here based on the functionality of this generator in combination with wind turbine and selected control system, the speed of machine as entering and three-phase current of machines as output is considered for turbine-generator. Thus, the equations will change as (11), (12) and (13) [50], [51].

$$i_{ds} = \frac{\frac{1}{s}(-v_{ds} - R_s i_{ds} + \omega_e L_q i_{qs})}{L_d} \quad (11)$$

$$i_{qs} = \frac{\frac{1}{s}(-v_{qs} - R_s i_{qs} - \omega_e L_d i_{ds} + \omega_e \lambda_M)}{L_q} \quad (12)$$

$$I_S = \sqrt{i_{ds}^2 + i_{qs}^2} \quad (13)$$

The power delivered to the load can be calculated by (14) and (15).

$$P_S = P_m - P_{cus} = T_e \frac{\omega_e}{p} - 3R_s I_S^2 \quad (14)$$

$$P_S = P_m - P_{cus} = T_e \frac{\omega_e}{p} - 3R_s I_S^2 \quad (15)$$

2.3. Control system

The inverter control system is used to control active power and reactive power injected to the network and maximum control is shown in Figure 4. The control system has two parts: i) MPPT, and ii) active and reactive power control of the exchange with the network.

2.3.1. MPPT control system

There is need for MPPT control for adjusting the speed of rotor to get the highest power from wind turbine [52]–[61]. Because the output voltage is not constant and it become short-circuit because of the switches sometimes, for controlling signal we use capacitor voltage which is constant.

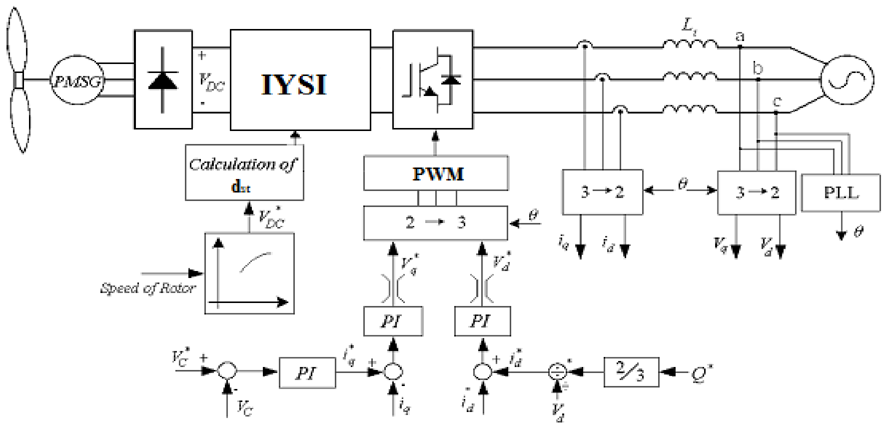


Figure 4. The control system considered for the proposed wind turbine system

The equation (16) shows the relationship between capacitor (C_2) and output voltage [51], [62], [63].

$$V_{C_2} = (1 - D)V_o \quad (16)$$

And according to the equation $V_o = \frac{1}{1-D(1+1+n_{21}/1-n_{32})} V_{in} = BV_{in}$ and placement in the above equation, the relation between the capacitor voltage C2 and the input voltage is as (17).

$$V_{C_2} = (1 - D)\frac{1}{1 - D(1 + 1 + n_{21}/1 - n_{32})} V_{in}$$
$$V_{C_2} = (1 - D)\frac{1}{1-ED} V_{in} \quad (17)$$

Thus, the signal controller according to the number of courses intended for the windings is calculated as (18).

$$D_{sc} = \frac{V_{In} - V_{C_2}}{V_{In} - EV_{C_2}} \quad (18)$$

2.3.2. Control of active and reactive power delivered to the network

Active power (P) and reactive power (Q) obtained from (19) and (20).

$$P = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \tag{19}$$

$$Q = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \tag{20}$$

v_d, v_q is network voltage, i_d, i_q injected current to the network in the frame of reference *d-q*. If the reference voltage become as network voltage, then v_q=0. Thus, the equations (19) and (20) will change to (21) and (22) [51], [64]–[67].

$$P = \frac{3}{2} v_d i_d \tag{21}$$

$$P = \frac{3}{2} v_d i_d \tag{22}$$

From the (21) and (22), we realize that we can control active and reactive injected powers to the network by controlling id and iq. To do that there are two directions of control will be considered. In the first direction by adding the amount of reference for reactive power, id will be adjusted and the amount of reference of id to reach power factor the unit will be considered as zero. In the next direction by capacitor voltage in inverter mode or output voltage in converter mode for controlling the output active power, iq will be adjusted [62], [66], [68].

3. METHOD

In this section, to investigate wind turbine systems there is an opinion based on Y-source inverter, the system simulated is shown. We used MATLAB/Simulink for simulation as Figure 5. Simulation parameters are shown in Tables 2 and 3. Voltage curve DC based on rotor speed is shown in Figure 6. We use this curve to find highest point of power and control inverter. To find this curve firstly in a few different speed (0.6-1.26 p.u) rotor and in highest power delivered to the network, the speed of rotor and DC link voltage has been measured which is shown in red in the figure. Then a polynomial function is guessed based on that which shows DC link voltage behavior change with respect to rotor speed changes in all the speeds with a very good approximation and low error. For comparison the improved Y-Source converter has been simulated. The simulated circuit is shown in Figure 7.

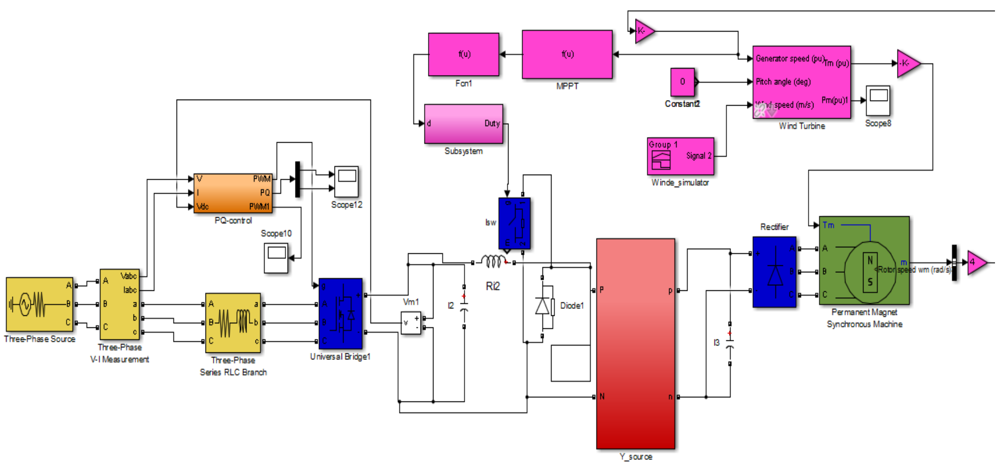


Figure 5. Simulated model in MATLAB/Simulink

Table 2. PM Generator Parameters

Amounts	Parameters
0.9585(Ω)	R
5.25(mH)	L_d, Lq
4	P
6329(kg.cm^2)	J

Table 3. Simulation Parameters

Amounts	Parameters
10(kHz)	Switching Frequency (F_s)
76(v))	Network Effective Voltage
0.5(mH)	Filter Capacitor (C)
20:41:20	Conversion Ratio (N_1:N_2:N_3)

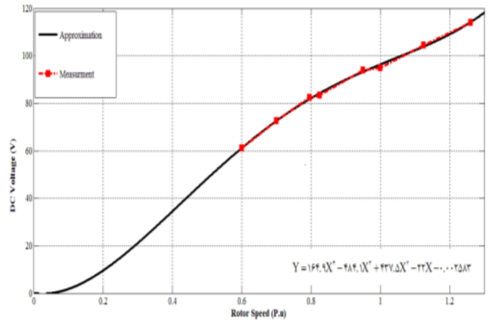


Figure 6. DC link voltage changes curve based on changes in rotor speed

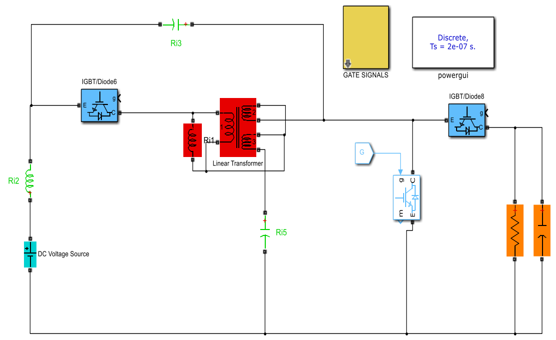


Figure 7. Simulated converter in MATLAB/Simulink software

4. RESULTS AND DISCUSSION

Wind model applied to the system based on Figure 4 which the speed reduces from 12 to 10 m/s. In Figure 8, changes in the speed of rotor by changing wind speed is shown in different time. Considering the curve of the changes in rotor speed and changes in wind speed curve, it is obvious that the speed of rotor has changed for delivering the highest power from turbine with the change of the speed of wind. To know these changes, we need to look at Figures 9 and 10, which in order they show mechanical and electrical curve. It is shown that after a short period of time the mechanical power curve of turbine production has reached the highest power and followed it (based on wind speed). DC link voltage inverter and its big scheme is in Figure 11. As it can be understood from Figure 11, voltage level changes from maximum to zero and vice versa, the reason of these changes are short circuits in the inverter bases in transition at the same time. Thus, in this situation, we use Y-source converter capacitor voltage to control MPPT and control active and reactive power which injected to the network. Inverter capacitor (C_1, C2) voltages is shown in Figure 12 and Figure 13.

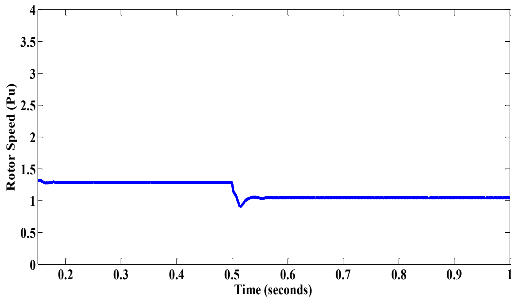


Figure 8. Rotor speed (p.u) according to variations in wind speed.

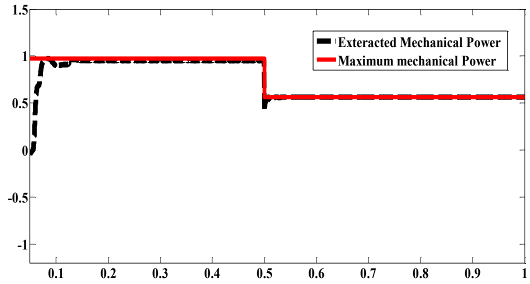


Figure 9. Curve of turbine mechanical power

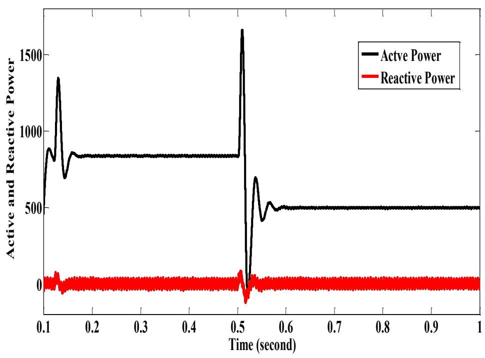
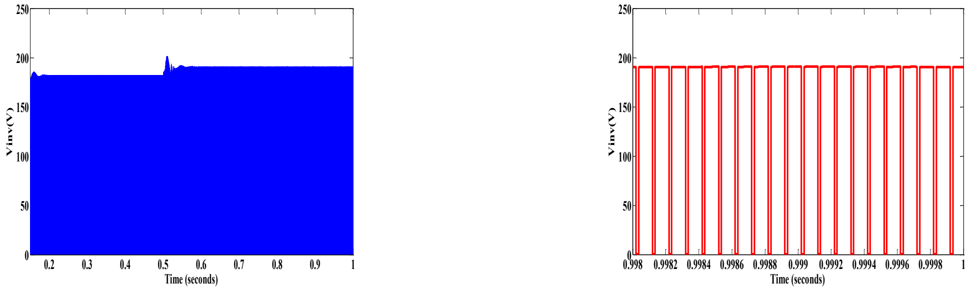


Figure 10. Active and reactive power which is delivered to the network under changes of wind speed.



(a) (b)

Figure 11. DC link voltage inverter, (a) Inverter DC link voltage, (b) Inverter DC link voltage in magnified mode under changes of wind speed

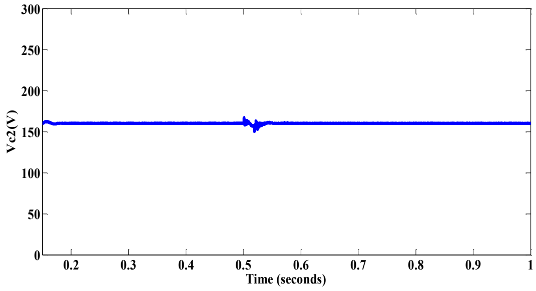


Figure 12. Capacitor voltage (C_2) under changes of wind speed

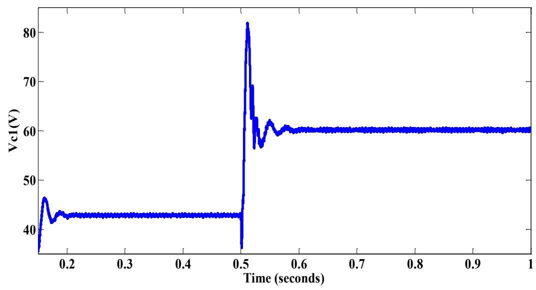


Figure 13. Capacitor voltage curve (C_1) under changes of wind speed.

Injection current to the network is shown in Figure 14. In order to obtain the system efficiency (η) at different wind speeds, we will first obtain the transmission power to the network and the maximum mechanical power at different speeds, and then from the relation of $\eta\% = \frac{P_{\text{grid}}}{P_{\text{max-mec}}} \times 100$, we will obtain the system efficiency. The power delivered to the network at wind different speeds and the efficiency of the proposed system are shown in Figure 15, and Figure 16, respectively. It is worth noting that this system could also be simulated based on the Y-Source DC-DC converter or the Improved Y-Source (DC/DC) converter, but this has led to the use of more switches and increased losses, and THD Also increases and it is not economically viable. Figure 17 and Figure 18 show that the system met the requirements for connecting to the network because the level of capacitor voltage is kept in a constant level and reactive power exchange to the network is almost zero (unity power factor).

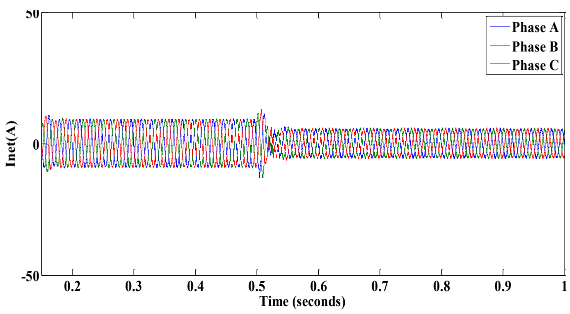


Figure 14. Injection current to the network by the proposed system

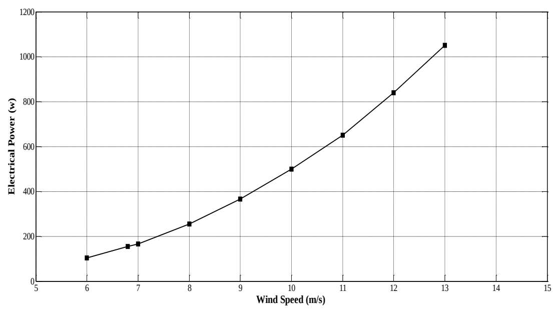


Figure 15. Power delivered to the network by the proposed system.

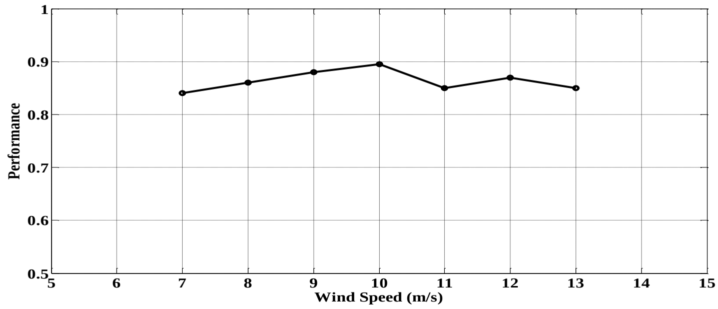
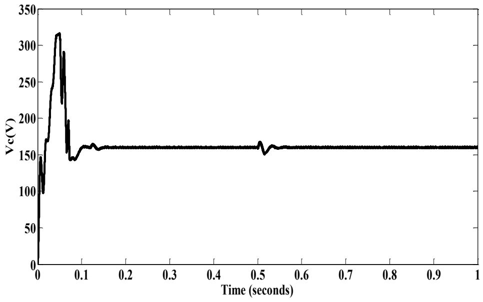


Figure 16. Performance of proposed system



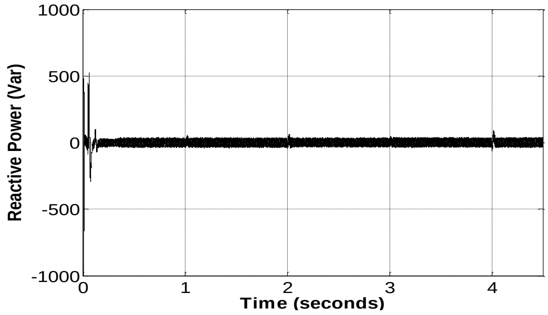


Figure 17. Capacitor voltage of Y-Source converter Figure 18. Reactive power exchanged with th network

4.1. Simulation of Improved Y-Source

Here, for comparison the improved Y-Source converter has been simulated and the results are presented. The simulated circuit is shown in Figure 7. The output voltage is plotted in Figure 19. The input current of the converter is plotted in Figure 20.

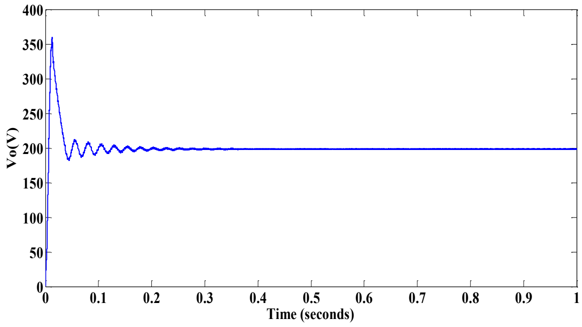


Figure 19. Output voltage of IYSI.

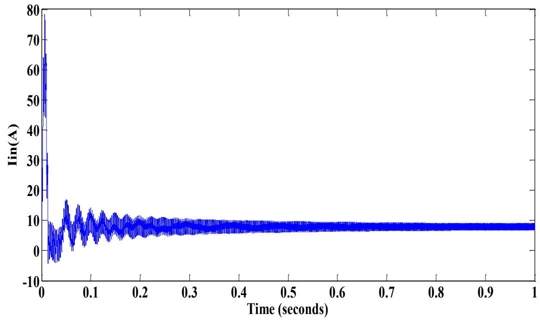


Figure 20. Input current of IYSI.

The voltage waveform of the capacitors is drawn in Figure 21. The voltage of the capacitors is obtained as (23) and (24).

$$V_{C_1} = (1 - D)V_o - V_{in} = (1 - 0.125) \times 200 - 100 = 75\ volt \quad (23)$$

$$V_{C_2} = (1 - D)\frac{1}{1-ED}V_{in} = (1 - 0.125)\frac{1}{1-4\times 0.125} \times 100 = 175\ volt \quad (24)$$

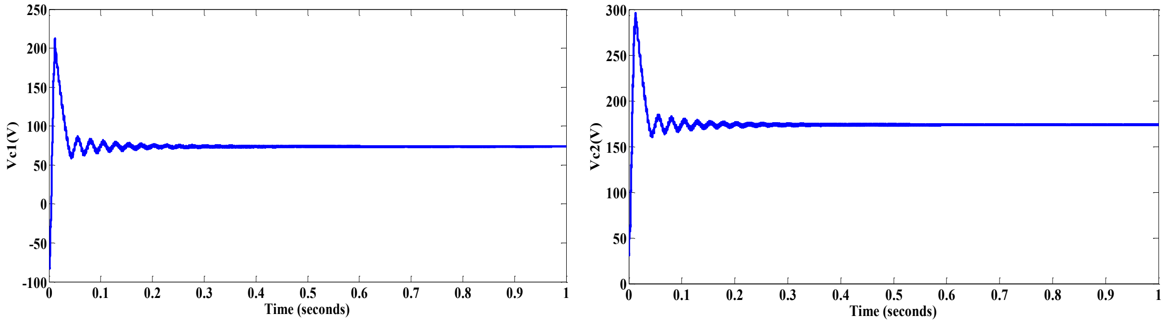


Figure 21. Capacitors voltage of IYSI (C_1, C_2)

4.2. Comparison results of the proposed system with other systems

In this section, the results of the proposed system of this article will be reviewed and compared with other systems. The proposed converter of this paper, as mentioned, has better features than the traditional Y-Source and corrects its disadvantages. First, the number of their elements is listed in Table 4. A comparison of the input currents of the two inverters IYS and IYSI is shown in Figure 22. As can be seen from the figure, the IYSI input stream is continuous and its ripple is negligible, which is a special feature along with other features of the YS family. Injection current harmonics to the network and the corresponding THD by the proposed wind turbine system including IYSI and wind turbine including YSI and wind turbine system based on Z-Source inverter are shown in Figures 23, Figure 24 and 25, respectively. Injection current of the proposed system in terms of harmonic spectrum, it performed slightly better than the traditional Y-Source system and provided better quality. Compared to the current harmonic spectrum of a system similar to the Z-Source electronic power converter, systems with the Y-Source family perform much better and have a lower THD harmonic spectrum.

Table 4. Structures compare of IYSI, YSI, ZSI.

Transformer	Number of inductances	Number of capacitors	Semiconductor number	Corverter
1	1	2	1	Improved Y-Source inverter
1	0	1	1	Y-Source inverter
0	2	2	1	Z-Source inverter

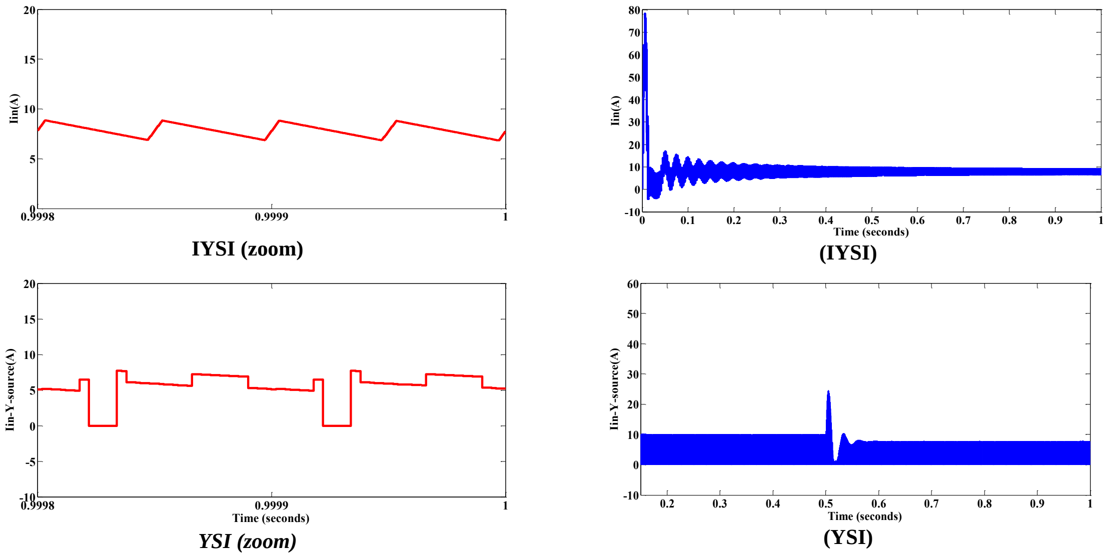


Figure 22. Comparison of the input current of IYSI and wind turbine system including YSI.

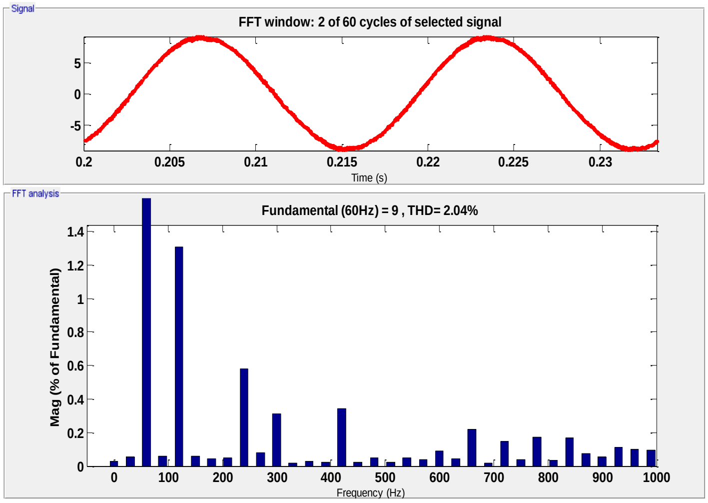


Figure 23. Injection current harmonics to the network and THD (IYSI)

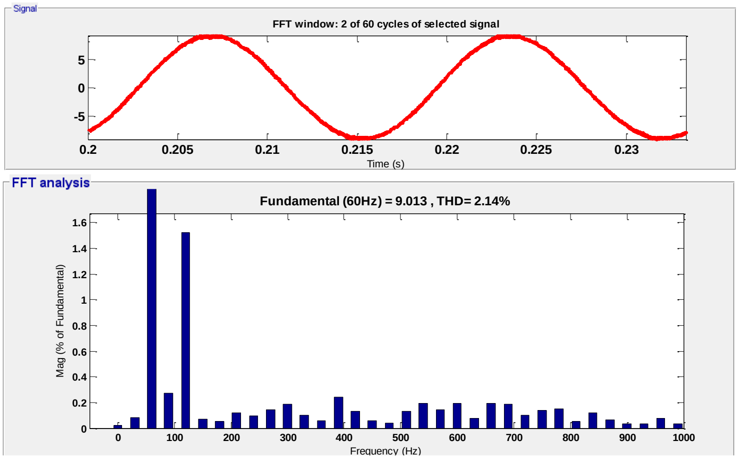


Figure 24. Injection current harmonics to the network and THD (YSI)

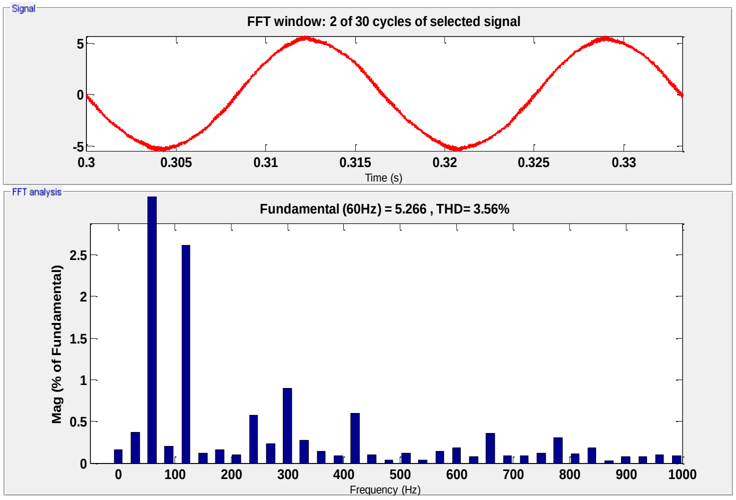


Figure 25. Injection current harmonics to the network and THD (Z-Source)

Numerical comparison of the proposed system THD with systems including traditional Y-Source and Z-Source is given in Table 5.

Table 5. Numerical comparison of THD (IYSI, YSI, ZSI)

THD	Converter
2.04%	Improved Y-Source inverter
2.14%	Y-Source inverter
3.56%	Z-Source inverter

5. CONCLUSION

As mentioned before, environmental factors such as air pollution and the increase in global warming by using polluting fuels are the most important reasons of using renewable and clean energy that runs in global community. Wind energy is one of the most suitable and widely used kind of renewable energy which had been in consideration so well. In this paper, we discussed a new structure of wind turbine based on Y-source inverter as connector between the network and generator. All parts of the suggested system were discussed and at the end the result of simulation which it was done by MATLAB/SIMULINK software were shown. The result shows the correct functionality of the system and controlling system under changes of the wind speed.

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